

"A Practical Method for Aircraft Life Enhancement"
(STTR 97-142)

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This report has been reviewed and approved for release on 10 April 1998. Interim reports 1, 2, and 3 may be reviewed for specific details regarding this research effort.



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Topic: AF97-142 Structural Integrity of Aging Aircraft

Summary

Purpose: The purpose of this Phase I effort was to prove the feasibility of reducing dynamic loads induced into aircraft structure by increasing landing gear strut precharge pressure. Reducing dynamic loads will reduce fatigue damage to aircraft structure resulting in life extension and reduced maintenance and inspections. An additional purpose of this effort was to determine the "degree" of life enhancement that can be achieved. Finally, commercial aircraft operations and maintenance organizations were contacted to determine the level of ground loads related problems that occur in day to day operations.

Description of Work Performed: A NASA Langley instrumented A-6 main landing gear strut was used to experimentally validate the concept. Computer simulations were used to predict dynamic load reductions for a large matrix of conditions for a variety of aircraft. The computer predictions were used to assess the potential life enhancement that could be achieved. Questionnaires were sent to a variety of commercial airline organizations requesting information regarding maintenance, inspection and structural failure data that relate to this effort.

Results: Phase I of this effort proved conclusively (both analytically and experimentally) that ground loads can be reduced by 40% or more by increasing strut precharge pressure. Estimated improvements in life of up to 15% were calculated for a randomly selected structure. A "hot spot" would show much greater improvement. The results of Phase I were better than anticipated.

Potential Applications: The application of this technology will include military and civilian aircraft. The aircraft that will benefit the most will be large flexible aircraft such as commercial jets and military bomber and cargo aircraft that operate heavy and on rough runways. The attractive feature of this approach is that significant improvements in life can be achieved with no modification to the aircraft structure. The only change is to modify the strut servicing procedure.

1. Concept Explored in Phase I

Phase I of this research effort explored the concept of reducing loads induced into an aircraft's structure by a non-intrusive technique which modifies the landing gear struts' servicing procedure. If the loads going into the structure can be reduced, the life of the aircraft can be extended and the costs associated with the inspection, repair, and modification process can be reduced. Typically, landing gear strut designs are *optimized* for landing impact loads, not the ground loads produced during taxi, takeoff, and landing rollout. This modified strut servicing procedure is to increase the strut's precharge pressure. Precharge pressure is the dry air or nitrogen pressure measured when the strut is fully extended. Essentially, increasing strut precharge pressure results in more "stroke remaining" and a softer ride when the aircraft has "weight on wheels". If more stroke is remaining, the strut has more capability to absorb loads induced by runway roughness.

Phase I also investigated the potential improvement in remaining life that can be achieved with a reduction in ground loads. In addition, Phase I investigated the amount of current maintenance activity that could be related to ground loads and potentially reduced if ground loads were reduced. Below are the results of the Phase I effort.

Experimental Results: Phase I has proven the feasibility of reducing ground loads by increasing strut precharge pressure. Figure 1 is a photograph of the instrumented A-6 main landing gear test setup at NASA Langley that was used to prove the concept experimentally. Figure 2 is one test result in which loads were reduced by more than 30%. A square wave was used for the tests. These experimental tests have proven conclusively that significant load reduction can be achieved with a moderate increase in strut precharge pressure. More detail on these experimental results can be found in the Phase I Interim Report Number 2.

Simulation Results: The experimental tests conducted at NASA Langley validated the concept for a single strut. Aircraft dynamic model simulations were conducted to predict the potential loads reduction that could be achieved for the aircraft as a whole. The dynamic model responds to measured runway profiles, and estimates the accelerations at the aircraft center of gravity (CGA – also called load factor) and pilot station (PSA). A matrix of aircraft/runway/strut pressure conditions were simulated. Table 1 is a summary of the results of the conditions simulated. In all cases, the overall ride quality index (RQI) was improved. In one case, the peak load factor at the center of gravity (CG) slightly increased when the higher pressure was simulated. Closer inspection of this showed that the peak occurred at a different time, hence a different bump in the simulation. The overall ride quality index decreased as expected. All other cases show "across the board" improvements for the pilot's station (PSA) and CGA. The CLASSB3 aircraft showed significant improvement for all cases simulated. Peak load factor reductions of 30 to 40% were typical. In addition, the overall ride quality index showed a 30 to 40% improvement. This is important to note because it shows that loads are reduced at all frequencies.

Several simulations were conducted using under serviced strut pressures, which happens frequently in the real world usage. (See Southern Air Transport's comments regarding strut maintenance in Phase I Interim Report #2.) In all cases, the load factors were increased

significantly. Under serviced struts will increase the loads induced into the aircraft and result in a reduced structural life. Phase I has shown that under servicing (low strut pressure) causes more fatigue damage to aircraft structure. Finally, aborted takeoff simulations were made on a runway that had a known dip in it. The purpose of these simulations was to show the excessive loads that can be imposed on the nose landing gear during this emergency operation. During an aborted takeoff, a maximum braking effort is used causing the aircraft to pitch down, loading up the nose landing gear strut and tires. Additionally, at higher speeds when the pilot holds the control column forward in order to increase nose wheel steering effectiveness and reduced chatter during the landing rollout or a high speed abort, the aerodynamic pitching moment increases the nose landing gear loading. In this loaded condition, most of the available strut and tire stroke are used up. Consequently, if a bump or dip is encountered, there is little, if any, stroke remaining to absorb the energy and the loads go directly into the aircraft structure. Simulations show that, for this condition, design limit loads (MIL-STD-8862A) can be exceeded on the nose landing gear and its supporting structure. As a result, the aborted takeoff operation on a rough runway can result in structural failure. As Table I shows, the higher precharge pressure struts dramatically improved the response in the aborted takeoff. Hence, improved safety in an aborted takeoff operation. The load factors are much worse if the nose landing gear strut is underinflated.

"Velocity sweep" simulations were conducted to show that improvements could be achieved at all aircraft velocities. Figure 3 shows the results of "velocity sweeps" over a typical 1-COS dip. This figure shows that peak CG and pilot's station vertical accelerations are reduced regardless of the speed at which the dip is encountered. This figure also indicates that a higher percent load reduction is achieved when the loading is more severe.

Active Gear Experimental Test Setup

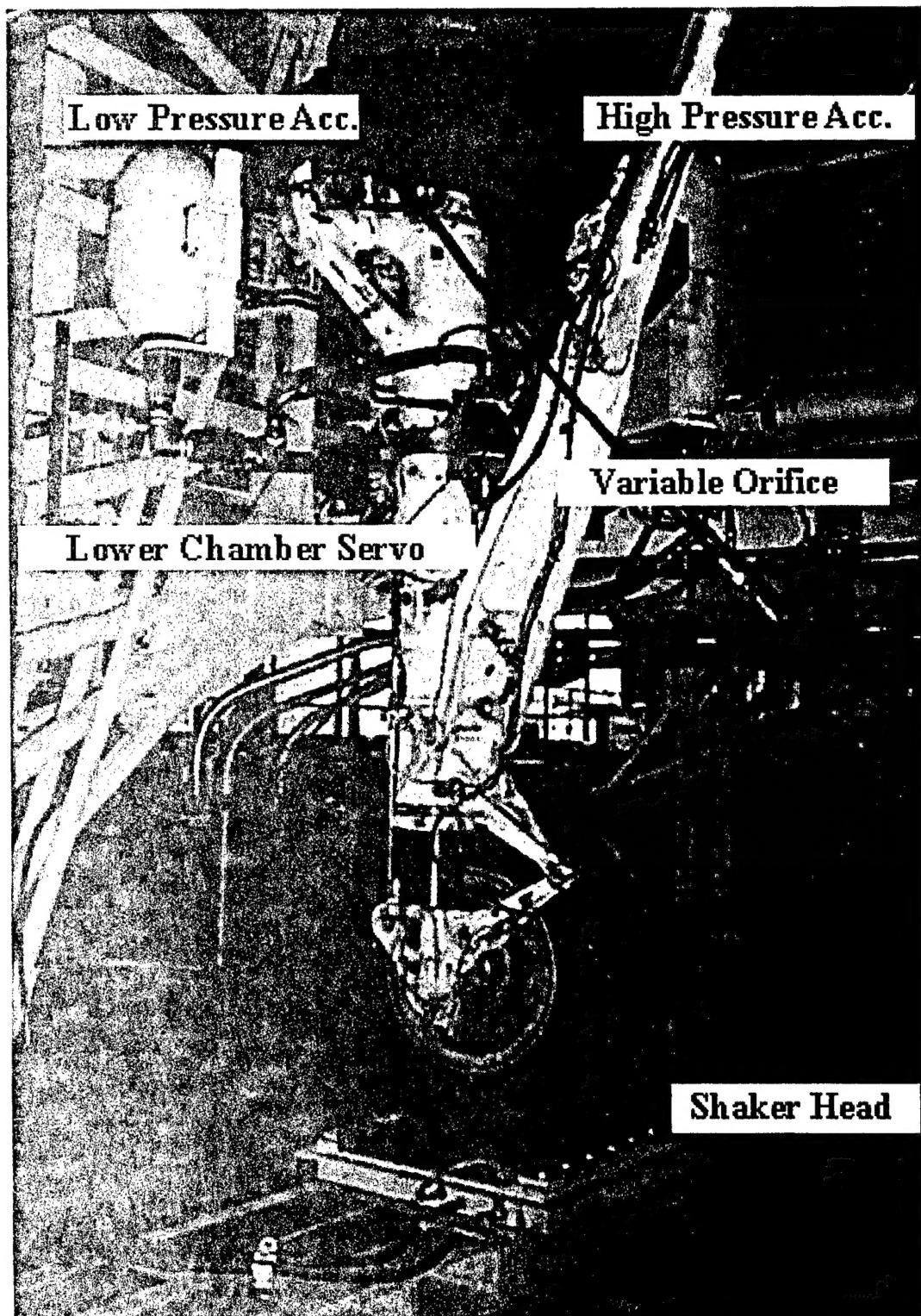


Figure 1. A-6 Main Landing Gear Test Setup at NASA Langley

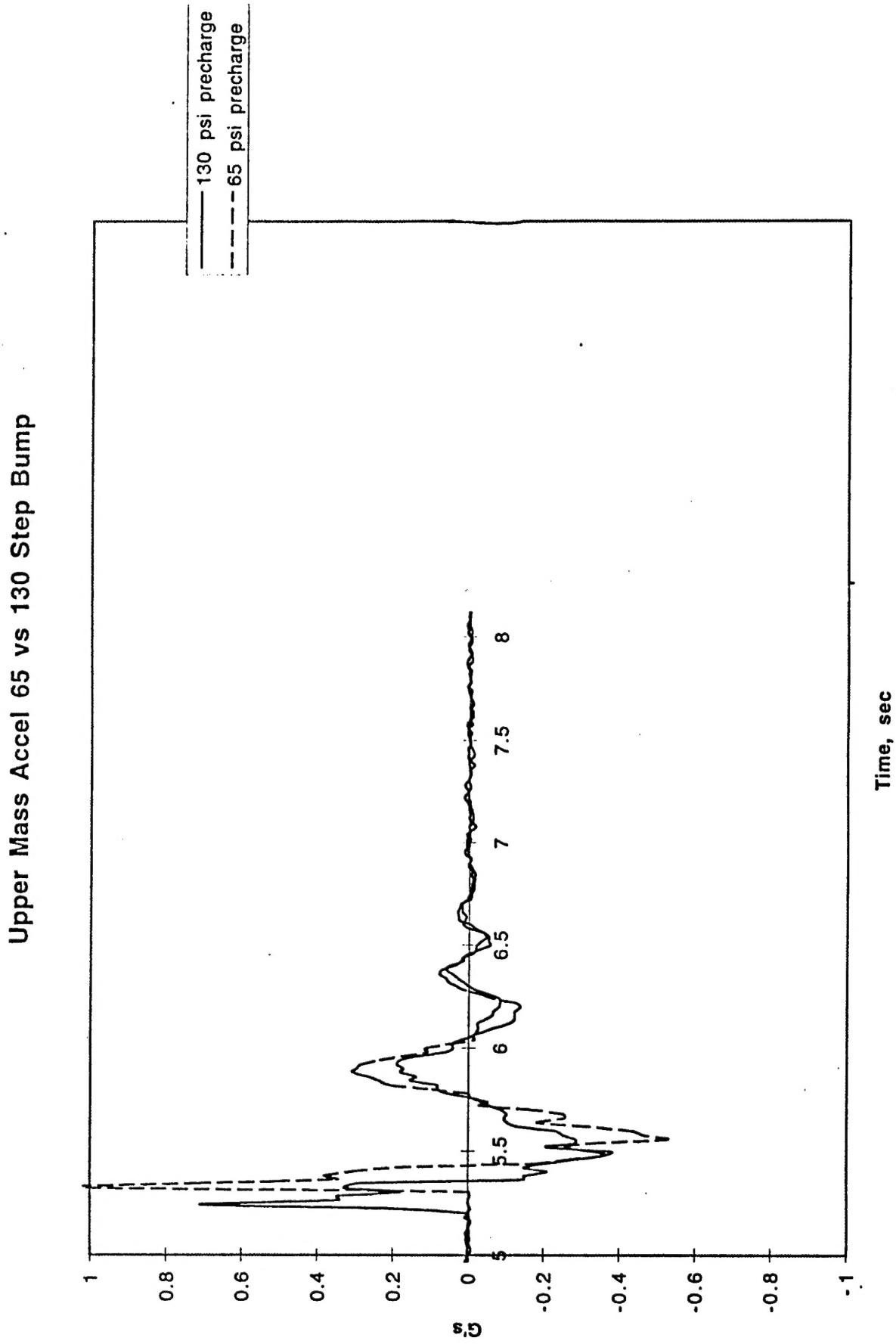


Figure 2. Comparison of Load Factor Results for High Pressure and Low Pressure Tests

Table I. Aircraft Takeoff Simulations

| Airplane | Runway | Strut Pressure (PSI) | Remarks | Results | | | | |
|------------------------------------|---------|----------------------|---|---------|-------|-----------|-------|-----|
| | | | | NI LG | ML LG | Peak(g's) | Total | RQI |
| <u>Normal Takeoff Simulations</u> | | | | PSA | CG | | | |
| CLASSB | ROUGH | 118 | Standard Precharge Pressure | .76 | .40 | 3.38 | | |
| CLASSB | ROUGH | 250 | High Precharge Pressure | .58 | .36 | 2.25 | | |
| CLASSB | ROUGH | 60 | Low Precharge Pressure (underinflated struts) | .95 | .83 | 4.64 | | |
| CLASSB | MIDWAY | 118 | Standard Precharge Pressure | .82 | .42 | 3.59 | | |
| CLASSB | MIDWAY | 250 | High Precharge Pressure | .77 | .58 | 3.48 | | |
| CLASSB3 | ROUGH | 240 | Standard Precharge Pressure | 1.02 | .78 | 4.45 | | |
| CLASSB3 | ROUGH | 350 | High Precharge Pressure | .61 | .42 | 2.91 | | |
| CLASSB3 | ROUGH | 120 | Low Precharge Pressure (underinflated struts) | 1.29 | .80 | 6.59 | | |
| CLASSB3 | MIDWAY | 240 | Standard Precharge Pressure | 1.12 | .78 | 4.41 | | |
| CLASSB3 | MIDWAY | 350 | High Precharge Pressure | .79 | .41 | 3.09 | | |
| <u>Aborted Takeoff Simulations</u> | | | | | | | | |
| CLASSB | NORFOLK | 118 | Standard Precharge Pressure (ABORT) | 1.42 | .75 | 5.75 | | |
| CLASSB | NORFOLK | 250 | High Precharge Pressure (ABORT) | .80 | .50 | 4.19 | | |
| CLASSB | NORFOLK | 60 | Low Precharge (underinflated struts) (ABORT) | 1.86 | .94 | 7.83 | | |

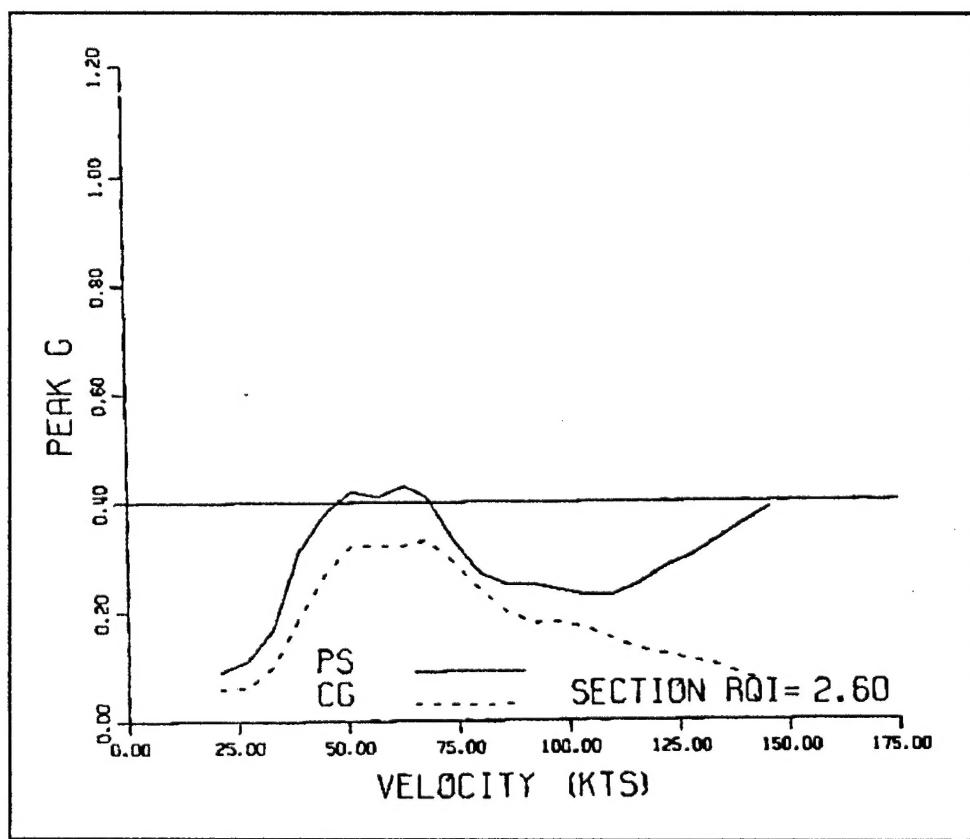
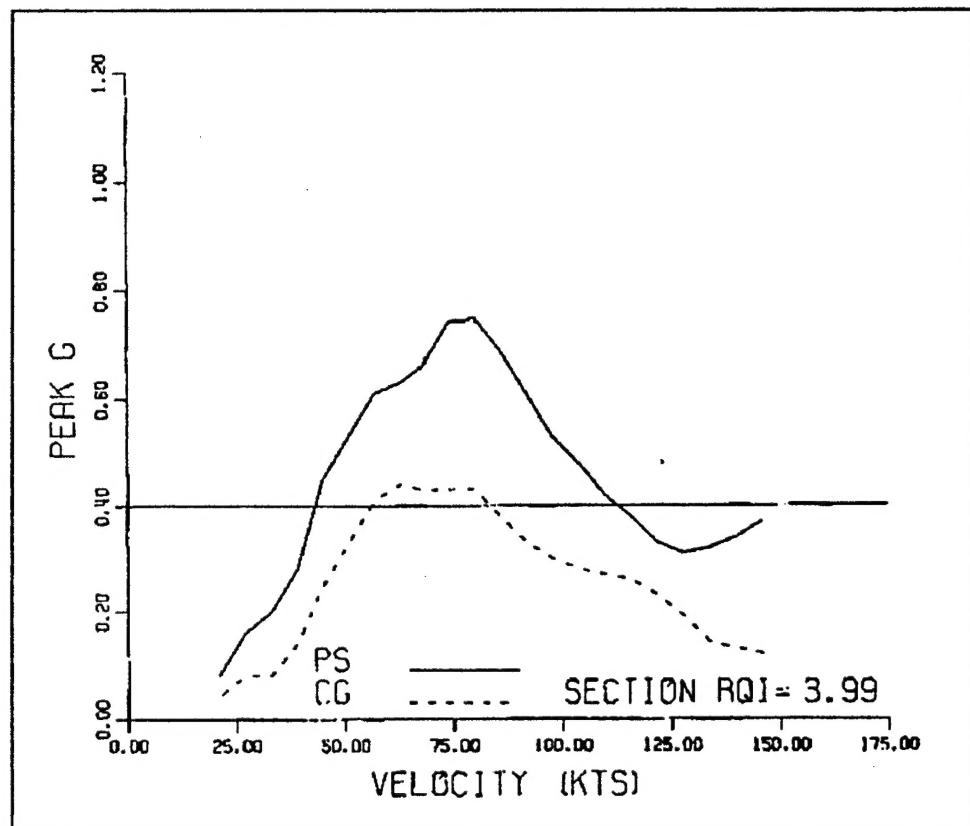


Figure 3. Velocity Sweep Results using Standard Precharge Pressure Struts (Top) and Increased Precharge Pressure Struts (Bottom)

Life Enhancement Predictions: The objective was to estimate the fatigue life improvements associated with reductions in airframe internal loads caused by runway roughness. This was accomplished by estimating relative fatigue damage values (referred to as a damage index or Life Factor). The Life Factor gives a measure of the damage associated with a selected spectrum relative to the damage for a specific spectrum.

As discussed previously, the accelerations at the center of gravity (also referred to as load factor or Nz) have been estimated from dynamic model simulations responding to actual runway and taxiway measured profiles. Figure 4 summarizes the influence of strut pressure on Nz occurrences due to runway roughness. Note that as strut pressure increases, the frequency of occurrence for the higher magnitude Nz's is reduced, and the frequency of occurrence for the lower magnitude Nz's is increased. Lower Nz means lower internal airframe loads such as those at the wing root. Recall that fatigue crack initiation and growth material properties include an endurance limit or threshold, below which no damage is incurred. Thus, more occurrences of lower magnitude Nz's is less damaging. The presentation of takeoff simulated Nz's as in Figure 4 becomes a quick means to judge the influence of improved strut servicing procedures on the fatigue life of some airframe components.

The development of an airframe spectrum from Nz histories must include the proper identifying of closed loop load cycles. This is accomplished by cycle counting the Nz data discussed above for the takeoff simulations combined with flight loads. The cycle counting of each takeoff simulation combined with a flight must be done to assure correct GAG cycle definition. Transport airframes are typically designed with low stresses such that the GAG is the only damaging event in the spectrum. The GAG cycle being defined by combining the maximum and minimum load values which occur throughout the Ground to Air to Ground events for a complete flight. In Figure 5, the cycle counted wing root loads are shown for the three takeoff simulations, each combined with a recorded flight. Note the resulting GAG cycles defined for the three cases. The increase in strut pressure causes the GAG cycle to shift to a lower alternating load with a higher mean load. The fatigue life factors (ratios) being most influenced by the alternating portion of the GAG cycle, therefore, indicate an increase for higher strut pressures. A life factor of about 1.15 (15% improvement) is estimated for a high strut pressure configuration as compared to a baseline configuration using a low (improperly serviced) strut pressure (see Phase 1 Interim Report #3). Even more improvement is anticipated for "Hot Spots" that are known to be affected by ground loads.

Figure 6 (2 pages) contains a flow chart of the process of using simulation predictions to predict life enhancement.

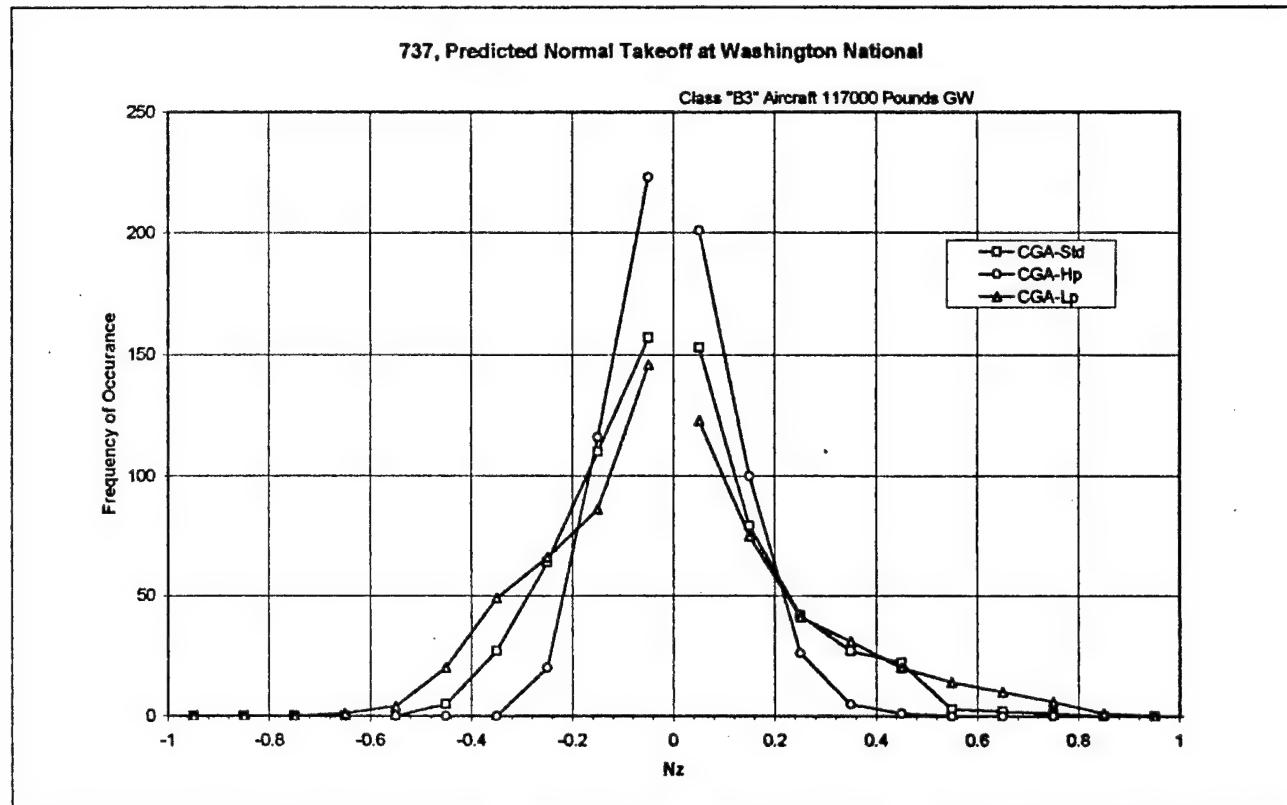


Figure 4. Frequency of Occurrence for Predicted Accelerations at the Center of Gravity (CGA) for a Normal Takeoff of a Boeing 737 with Standard (Std), High (Hp), and Low (Lp) Strut Pressures Using a Measured Runway Profile for Washington National Airport.

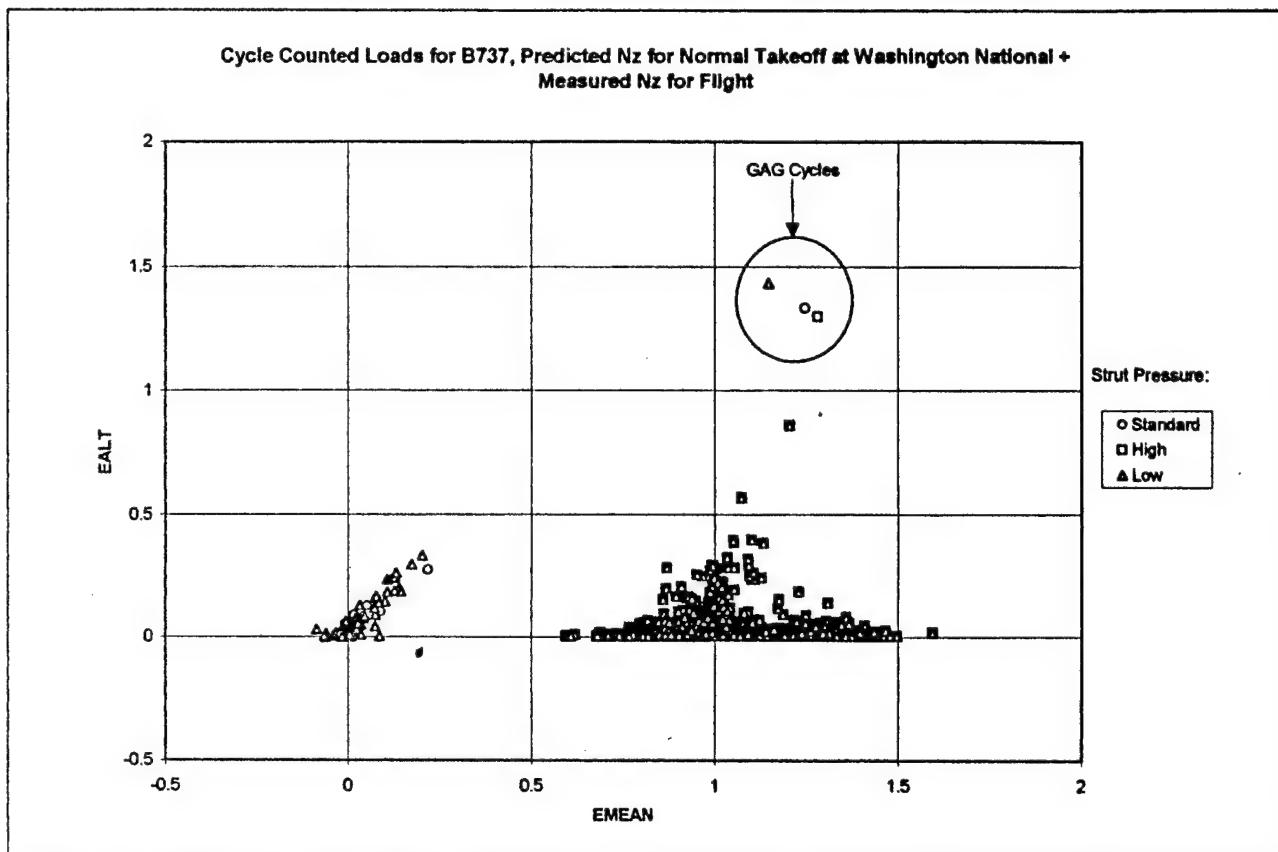


Figure 5. Estimated Wing Root Loads, Alternating (EALT) versus Mean (EMEAN), for a Boeing 737 from Predicted Nz for a Normal Takeoff from Washington National Plus Measured Nz for a Normal Flight. Predicted Nz during the Takeoff Segment included Standard, High, and Low Strut Pressure.

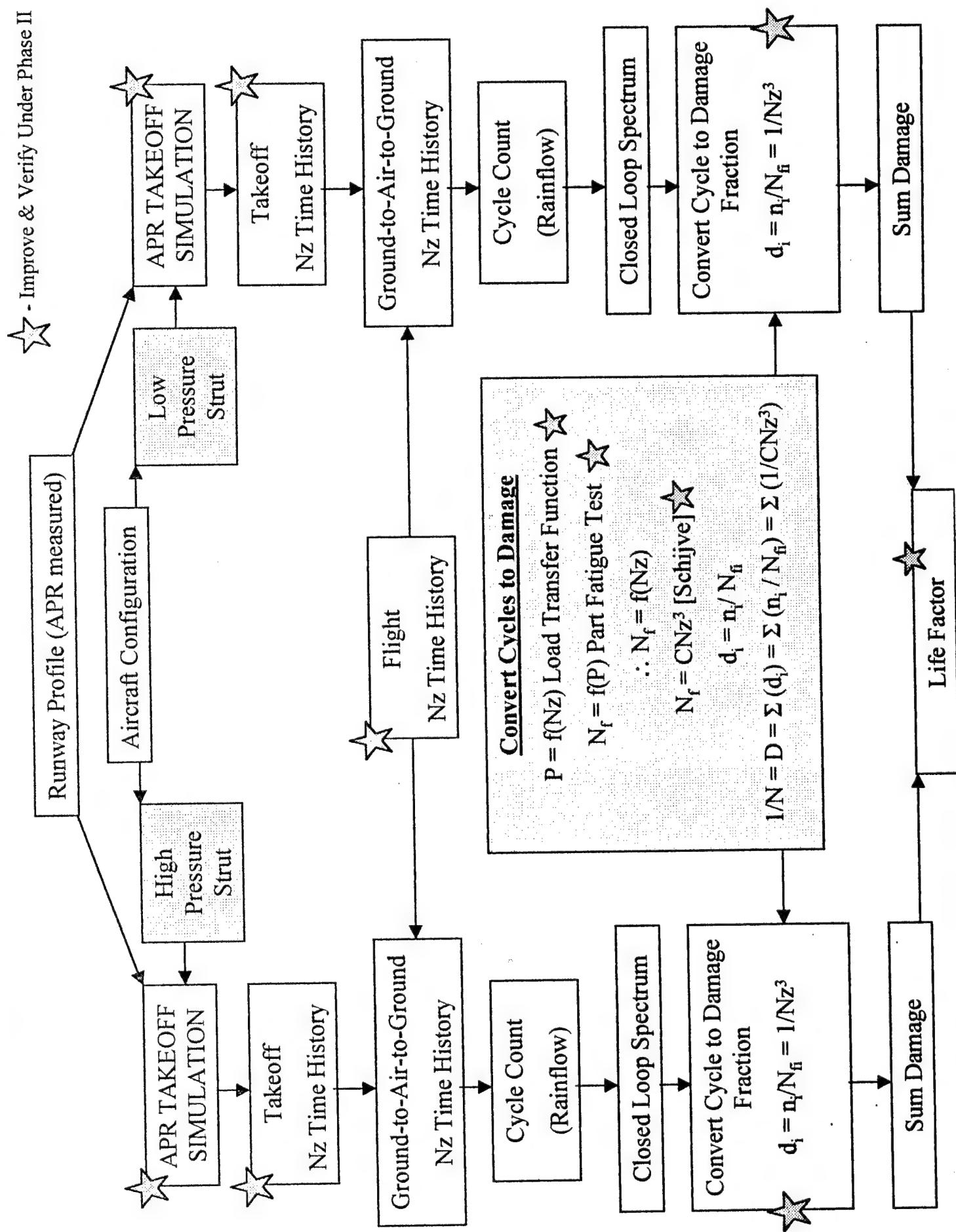


Figure 6. Flow Diagram of Life Enhancement Prediction Process

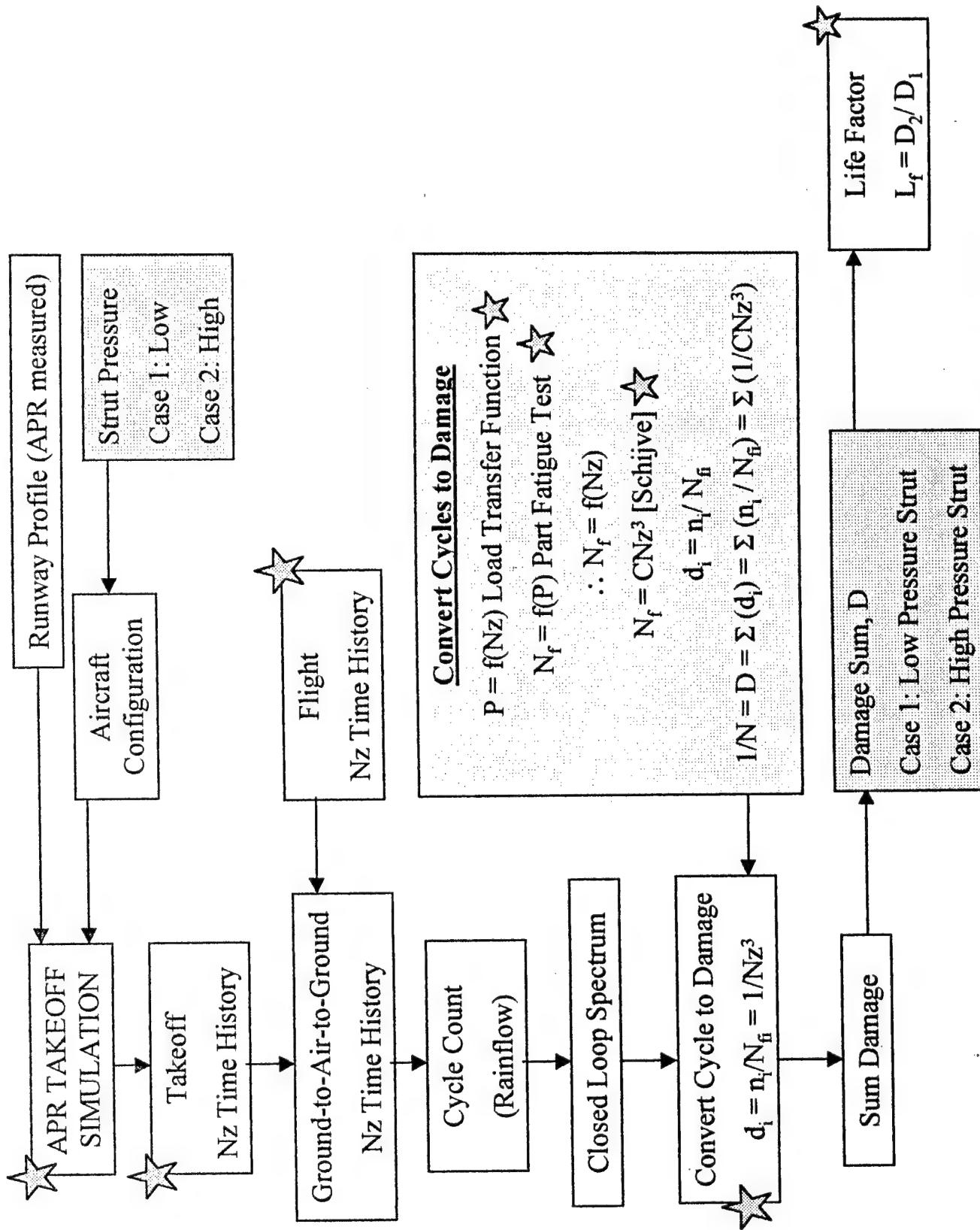


Figure 6. Continued

★ - Improve & Verify Under Phase II

Current Maintenance Activity: The military and civil aviation communities both rely very heavily upon a system of inspections, repairs, and modifications. When an aircraft is first developed, a series of design analyses and structural tests are conducted to establish the limit loads and periodic inspection cycles.

The inspections go by different names in the two aviation communities, but they serve similar purposes. Where the military has preflight (BPO), Isochronal, and Depot level inspections, the civil community has Service, A-, B-, C- and D-checks. For example, the BPO and Service Checks occur every few days and are allowed to remain valid for a period of time; typically for 3 days. The other inspections are tied to either flight hours or months since the previous inspection at that level, and keep the aircraft out of operation for longer periods of time due to the level of scrutiny. A B-check may be just to examine the equipment on an aircraft; they usually take place on the flight line, and only require an overnight shift to accomplish. On the other hand, an Isochronal inspection or C-check makes a more detailed examination of aircraft structures and engines, and may occur every couple of years or thousands of flight hours, and requires a hangar since the aircraft may be out of service for 30 days or more. At the highest level are the Depot and D-checks. While it could be argued that this system enhances aircraft service life, the primary purpose is only to ensure airworthy aircraft are in operation. Repairs and modifications are made only in response to problems discovered, and, therefore, have no preventative life enhancing nature.

One possible fallacy of the BPO and Service Check philosophy was discovered during Phase I of this study. The Boeing 747 landing gear service procedure calls for checking and re-servicing the struts after every 5-10 landings due to the dry air/nitrogen precharge being absorbed into the hydraulic fluid. When this occurs, the strut is less able to absorb the energy of landing impacts due to oil foaming. The strut is essentially under-serviced and higher ground loads are also likely to result. If the B747 strut service interval is typical for transport aircraft, then loads imparted to the airframe from the landing gear may not be properly accounted for. During military pilot proficiency training sorties, the crew can easily accomplish 20 to 30 landings during the course of a 4-hour mission. Civil aviation in-aircraft training practices are unknown, but it is not unusual for some aircraft like the B737 or DC-9 to log 5 landings or more during a normal day of commercial operations.

A recent example also discovered in Phase I, demonstrates that the manpower, time, and test equipment intensive inspection method of assessing aircraft structures is not infallible. Within the past 2 years, a Lockheed L-1011 was taxiing to parking following its final landing when it started to leak fuel. When the area in the vicinity of the leak was inspected, a 24-inch long crack was found in the web of the rear wing spar and stopped behind the main landing gear trunnion. An interesting part of this incident is that this area of the L-1011 has been under close observation for at least the last decade.

When unusual problems are discovered during the normal inspection cycle, or as a result of an in-service incident, there is a special system to resolve it. Under this system, a series of out of cycle inspections, repairs, or modifications may be directed in a special notice called an Airworthiness

Directive (AD) which is issued by the Federal Aviation Administration (FAA). These required actions may be tied to the number of landings, pressure cycles, flight hours, etc. or a combination of factors. Generally, ADs apply to all aircraft with the same type certificate. For instance, a crack may be discovered in the wing skin and aft spar near the MLG attach point. After analysis, public hearing(s), and an opportunity for comment, the FAA issues an AD which directs an inspection of all aircraft of that type be conducted. The inspection may be tied to a period of time following the issuance of the AD, or tied to other criteria as mentioned above, and may become recurring. If problems are discovered during the inspection, the aircraft operator usually has the choice of repairing the damage or seeking approval to modify the affected structure. The exception to AD applicability occurs when multiple ADs issued over the years affect the same aircraft structure, and an operator previously chose to modify it in accordance with an approved method.

During Phase I, landing gear and structural data were gathered on several aircraft including the Lockheed L-1011. It was discovered that since 1976, 14 ADs were issued in response to in-service problems related to the landing gear or primary aircraft structure in the vicinity of the gear. There is a report, unsubstantiated as of now, that in the mid-1980's the MLG strut *precharge was increased* to combat aft wing spar cracking. Except for this one possible case, the ADs which were examined during Phase I do not appear to fully account for the impact that landing gear loads have on airframe service life. This implies that the damage caused by ground loads is not well understood.

Recent information collected from commercial operations and maintenance organizations are contained in appendix "A". This information is very recent, consequently, it has not been reported in any of the previous phase I progress reports. It is pertinent information and is therefore included as an appendix to this final report.

2. Additional Work Required Prior to Implementation:

Phase I has determined that the effect of ground loads may have a much larger effect on the fatigue life and cost of operation than previously expected. It is possible that design fatigue life calculations may have underestimated the damage inflicted by ground loads. This establishes the need for reducing ground loads.

Phase I has demonstrated the feasibility of the proposed concept to reduce ground loads by 30% to 40%. Now that the concept has been proven, additional effort is required for implementation on military and civilian aircraft.

Landing Impact: A more thorough investigation is required to determine the effect of high-pressure struts on aircraft landing impact dynamics and the effect on landing gear strut maintenance.

The computer program STRUT was modified in Phase I to simulate a drop test (landing impact) of a single A-6 main landing gear strut. This was a limited analysis and the modified version of STRUT has not been validated with measured drop test data. Additional effort would compare

STRUT drop test predictions with measured data.

In addition, APR Consultants has developed and markets an aircraft simulation program called LANDING. This program is designed to simulate aircraft dynamic response to runway roughness during landing rollout. The current version does not consider landing impact. Additional effort would include modifying the existing version of LANDING to include landing impact with sink speed and strut pressure as variables. This program could then be used to predict landing impact dynamics for the aircraft as a whole.

Fatigue Life: Reasonable accurate life factor estimates from a validated analytical process are essential for realizing improvements in usable life (readiness) and R&M costs. A validated analytical process will be useful in providing cost-effective estimates of fatigue factors for a broad range of aircraft, which could benefit from improved strut servicing procedures. The validation process will require collecting measured Nz data from a selected aircraft covering all phases of a flight (particularly the takeoff and flight phases). This will provide measured data for two purposes. First, to validate the dynamic model simulation of the takeoff phase. Second, to provide a better relationship for converting Nz to component load for a critical airframe structure suffering from fatigue damage.

A C/KC-135 fleet has been identified as a likely candidate to provide the needed ground and flight measured Nz data. Flight Data Recorders (FLDR) were installed on approximately 60 C/KC-135 aircraft and began recording data in early 1986. The FLDR system for the C/KC-135 collects typical performance and flight profile data as well as strains for four structural components. The flight profile data includes accelerations at the center of gravity (Nx, Ny, and Nz), rotations at the center of gravity, and position of landing gear and aerodynamic control surfaces. The strain gage locations include 1) inboard wing spar aft pylon near the attachment to the main landing gear (MLG) support frames, 2) support structure over the MLG, 3) center wing, 4) tail section. The USAF continued support for this FLDR system through 1990. At this time, the USAF is not funding efforts to record and retrieve the FLDR system data, but the system is still installed and thought to be functional. USAF Technical Order TO-1C-135-38 provides descriptions of the FLDR system, the installation, and affected aircraft tail numbers. The FLDR system on the C/KC-135 is thought to be a flight only data recorder since the FLDR TO indicates a recorder on/off switch which is triggered on when the MLG position is up. The historical flight data will still provide information to better establish a relationship for converting Nz to component load for a critical airframe structure suffering from fatigue damage (such as the wing spar aft pylon). In order to obtain measured ground data to validate the takeoff simulation, a C/KC-135 equipped with a FLDR system could be turned on for ground recording during normal operations. This would be non-intrusive to the operations of the aircraft and would only require minimal USAF assistance to validate the proper functioning of the FLDR system. This same aircraft could then be used to collect ground FLDR system data when the influence of defined runway roughness is investigated.

Build Maintenance Data Base: Additional effort would include, continued investigation into aircraft and landing gear data bases. The investigations will zero in to the specific aircraft on which the high-pressure strut concept will be demonstrated. Data will be collected from the

aircraft depot, the landing gear depot, and the landing gear manufacturer, as well as an operational unit, to provide insight into structural cracking, landing gear failure mechanisms, and monitoring implementation of the concept on a limited fleet.

Surprises in Phase I; There were a few surprises in Phase I. For example, the importance of under-servicing struts was underestimated. Simulations indicate that an aborted takeoff with the nose landing gear under-serviced is likely to exceed the design criteria of MIL-STD-8862A, if moderate runway roughness is encountered.

Another surprise was the tracking parameter inconsistency: Different aircraft use a variety of tracking parameters to establish inspection procedures. The parameters are generally based on time, GAG cycles, landings, or combinations thereof. It was discovered that in at least one instance, all landings are not considered equal (2 unpressurized touch-and-go landings = 1 pressurized full stop landing). Some events could be missed or not accounted for in the tracking databases.

Still another example is the L-1011 crack(s) in and around the main landing gear, and the fact that the unsubstantiated fix was to increase strut pressure.

The surprises of Phase I seem to indicate that ground loads may play a larger role in fatigue of airframe and subsystems than previously suspected.

3. Required Additional Effort Technical Objectives:

The specific objectives for additional effort are as follows:

1. **Modify existing simulation software to include landing impact:** The computer program STRUT was modified in Phase I to include landing impact. Additional effort will refine the model with drop test data. APR's existing computer program, LANDING, will be modified to conduct landing impact and rollout simulations.
2. **Determine the effect of increased precharge pressure on landing impact dynamics:** Phase I produced unsubstantiated reports that the airline industry has utilized this proposed concept before on the Lockheed L-1011 to combat aft wing spar cracking, and no reports of negative effects due to the increased precharge pressure have been encountered to date. This operational experience is extremely valuable for implementation on a wide scale. This will be investigated in more detail. In addition, research should be conducted in an effort to fully examine landing impact dynamics for other aircraft as well as extreme conditions.
3. **Demonstration of the concept on an instrumented aircraft:** Phase I has shown by both simulation and experiment that increasing precharge pressure will significantly reduce loads in a single strut. Phase I simulations have also shown that, across the board, ground loads reductions can be achieved for the aircraft as a whole. Additional effort should demonstrate the ground loads reduction and landing impact loads using an instrumented aircraft. The proposed test aircraft is an FLDR (Flight Data Recorder) equipped KC-135.
4. **Estimated cost savings/life enhancement resulting from concept implementation:** An estimated cost savings will be performed for each candidate aircraft for implementation. The major costs of implementation are contained primarily in performing the analyses, updating the aircraft servicing documentation, and training; the cost of high-pressure servicing is practically nothing. Aircraft and landing gear maintenance data should provide excellent sources for repair costs (time and/or dollars). The savings estimates can use the historical data as a basis for determining the actual benefits (e.g., reduced inspections or repairs, increased aircraft availability, etc.). The estimates will also need to account for any adverse impacts such as premature wear of landing gear components.

4. Potential Applications of this Technology:

This concept for life enhancement has wide application to the military. It has been said that Desert Storm used up a large portion of the remaining life in the USAF cargo and support aircraft fleets. If implemented, this concept will reduce additional damage. All flying services of the military would benefit from the savings and improved operational capability. The implementation process will consist of working with the responsible maintenance organizations, determining the optimal precharge pressures to be used on each aircraft type through simulation and testing, and amending the appropriate strut service procedures. No structural modification is required. It is probable that implementation will be accomplished in a build-up approach through the use of

technology demonstration on operational FLDR instrumented aircraft. This approach will build a database to look at the long-term impact.

This concept also has wide commercial application both in the US and internationally. It is envisioned that all major air carriers would use this technique to minimize fatigue damage, reduce maintenance costs, and improve safety. The universal measuring stick which both the civil and military aviation communities can relate to is that the aircraft will have increased availability.

APR Consultant's strategy for converting the research into widespread commercial use will be to work with organizations such as the Air Transport Association (ATA), the Aerospace Industries Association (AIA), the General Aviation Manufacturer's Association (GAMA), the National Transportation Safety Board (NTSB) and the Airline Pilot's Association (ALPA).

5. Conclusions and Recommendations:

A concept for life extension of aging aircraft has been proven both analytically and experimentally. The concept is to increase landing gear strut precharge pressure in a manner that optimizes landing impact and taxi loading conditions. The concept is non intrusive, in that no structural modifications are required for fleet implementation.

Inquiries into the operational world have uncovered evidence that the ground loads issues have been underestimated and contribute more heavily to aircraft fatigue than anticipated. For example, the method of "counting cycles" does not reflect the true loading environment of the landing gear and it's supporting structure.

Additional work is required prior to implementation to examine the effect of increased pressure on extreme conditions of the landing impact envelope. In addition, field testing of the concept over an extended period of time under routine operational conditions is required to better define the payoff of implementation and expose technical difficulties, if any, as they occur.

It is recommended that this effort be continued and that the required additional work be completed for eventual implementation of the non intrusive concept. It is also recommended that the effect of ground loads on aircraft fatigue life be re-evaluated. Finally it is recommended that the method of counting cycles be examined when conducting "life remaining" calculations for landing gear and supporting structure.

Appendix "A"

Impact on Fleet Usage/Implementation

Objective: To build a data base on civil & military transport aircraft landing gear servicing procedures, airframe inspection intervals, and history of in-service structural cracking as a pre-concept implementation reference.

Continued follow-up with previous contacts to aircraft engineers (systems & structural) for American Trans Air (ATA) on Lockheed L-1011 and America West on Boeing 737. The requested data was the same as previously reported specifically tailored toward the landing gear and structural maintenance data on the target aircraft. The related inputs and findings are discussed below:

ATA: Unfortunately, ATA has been unable to research and provide the requested data due to manpower constraints. They are in the process of returning several previously mothballed L-1011s to service. ATA is the largest operator of L-1011s and, for the most part, performs their own engineering. However, ATA provided contacts at Lockheed whom they believe will be able to provide the requested information. Contact has been initiated, but no inputs have been received.

America West: Similarly, America West was unable to provide inputs on the Boeing 737 due in part to manpower issues. The other concern is the potentially proprietary nature of some of the Boeing data. However, contacts at Boeing Commercial Aircraft Company (BCAC) were provided. The BCAC input consisted of two parts: 1) aircraft inspection intervals and 2) landing gear servicing. Both are summarized below:

- Aircraft Inspection Intervals: When a new aircraft enters service, the inspection intervals (initial) are recommended by the manufacturer based upon engineering analyses and, to some extent, structural testing. BCAC provided an input on all its commercial aircraft since the inception of the B-707.

The tables shown below represent BCAC's recommendation and the worldwide average intervals based upon operator data inputs. The definitions of "A-", "B-", "C-", and "D-Checks" were previously reported and not repeated here. The Notes associated with the BCAC recommendations are not shown either. As a generalization, the Notes identified three things: 1) a blank means an inspection is not recommended or required, 2) a special or unique inspection interval applies to a single component such as the nacelles & pylons on the 737-300/-400/-500, and 3) an identifier such as "4C" means the fourth "C-Check" is more encompassing than the normal inspection & essentially replaces what would be considered a "D-Check".

BCAC Recommended Initial Inspection Intervals (Flight Hours)

| | A | B | C | D |
|-------------------|-----|-----|-------|--------|
| 707 | 90 | 450 | 1,800 | 14,000 |
| 727 | 80 | 400 | 1,600 | 16,000 |
| 737-100/-200 | 125 | 750 | 3,000 | 20,000 |
| 737-300/-400/-500 | 200 | | 3,200 | 22,400 |
| 747-100/-200/-300 | 300 | | 3,600 | 25,000 |
| 747-400 | 500 | | 5,000 | 25,000 |
| 757 | 500 | | 6,000 | |
| 767 | 500 | | 6,000 | |
| 777 | | | | |

Worldwide Fleet Average Inspection Intervals (Flight Hours)

| | A | B | C | D |
|-------------------|-----|-------|---------|---------|
| 707 | 156 | 540 | 2,126 | 17,756 |
| 727 | 156 | 590 | 3,154 | 20,672 |
| 737-100/-200 | 173 | 668 | 2,654 | 20,168 |
| 737-300/-400/-500 | 205 | 800 | 3,330 | 22,084 |
| 747-100/-200/-300 | 472 | 1,484 | 4,780 | 24,919 |
| 747-400 | 611 | 1,895 | 5,465 | 26,416 |
| 757 | 400 | | 4,000 | |
| 767 | 410 | | 4,203 | |
| 777 | 625 | | 2 Years | 4 Years |

From the tables above, two observations can be made. As a rule, the data provided to BCAC by the operators indicates that the time interval between inspections generally exceeds the recommendation. No determination has been made with respect to the level of structural damage discovered during inspections nor the long term impacts to fatigue life. Perhaps more interesting is that as the analytical tools available during the design phase & materials/manufacturing processes have improved, recommended inspection intervals have also increased.

- Landing Gear Servicing: BCAC's input which is related to landing gear servicing will be discussed below in three parts: 1) the importance of proper shock strut servicing, 2) B737 strut servicing, and 3) B757 strut servicing.

⇒ Proper Strut Servicing: As part of their input, BCAC provided an article entitled "Servicing Landing Gear Shock Struts" by Robert E. Ahern, Supervisor - Structures, Post Production Engineering. The article was published in the April-June 1986 issue of *Airliner* magazine.

The focus of the article is that when servicing shock struts, the correct amount of hydraulic fluid and proper dry air/nitrogen pressure are imperative in order to ensure optimal performance and prevent adverse impacts. Generally, this philosophy is evident in BCAC's recommended landing gear service procedures. However, later discussions on both the B737 and B757 will provide servicing and in-service examples which seem a little contradictory to their philosophy.

Following a short discussion of how a landing gear works, the article provided a hypothetical example of properly and poorly serviced struts. The strut which has been properly serviced with hydraulic fluid has fully compressed and extended dry air/ nitrogen pressures of 1500 psi and 187.5 psi, respectively. On the other hand, the poorly serviced strut has insufficient hydraulic fluid. While the compressed pressure is still 1500 psi, the excess dry air/ nitrogen volume required to compensate for the lack of oil results in a fully extended precharge pressure of 750 psi. This can result in damage to the inner cylinder components and retaining devices (gland nuts) after takeoff or during aircraft jacking. While this example appears to be an extreme case, it still raises some points to consider for concept implementation: 1) Proper servicing starts with proper oil serving, 2) there is some undefined limit to increased precharge pressures that needs to be taken into account, and 3) landing gear manufacturer and, perhaps component supplier, involvement is imperative for each aircraft considered.

The article cites some "real world" Boeing experiences with improperly serviced landing gear struts, but it does not provide specific details. The level of detail is that the strut had too little oil and too much air. In no instance was the strut ever underserviced with dry air/nitrogen. While this is indicative of the BCAC's philosophy toward landing gear service, it needs to be noted that only landing gear damage is addressed and not the potential impacts to the aircraft structure. Some B747 aircraft have blown MLG tires when a single strut was improperly serviced. Some early B737 aircraft experienced MLG shimmy and torsion link fracture during landing impact with improperly serviced struts. A final example does not mention a specific aircraft, but is based on the premise that a slight strut over-extension when servicing at high takeoff gross weights will result in increased over-extensions at lower landing weights. If the NLG is extended excessively during ground operations, the centering cams may contact each other during towing or taxi turns and result in internal landing gear damage. I can personally attest to having similar experiences with the last case while flying B707-type aircraft which fortunately did not result in aircraft damage. While not the result of an overserviced strut, a lightweight aircraft with an aft CG position does allow the NLG to fully extend rapidly and can result in the loss of nosewheel steering; needless to say, a very uncomfortable feeling when taxiing on slick, narrow surfaces (Boeing Field, Seattle, WA).

→ B737 Strut Servicing: BCAC provided a set of briefing charts on B737 strut servicing procedures, NLG servicing charts for -200 & -300 aircraft, and an MLG servicing chart for the -300 & -500 aircraft. While both the NLG & MLG procedures will be discussed here, only the MLG service chart has been recreated.

When the B737 NLG is serviced, it requires a specific sequence of raising/lowering the aircraft and compressing/extending the strut. This is critical to ensure that the space between

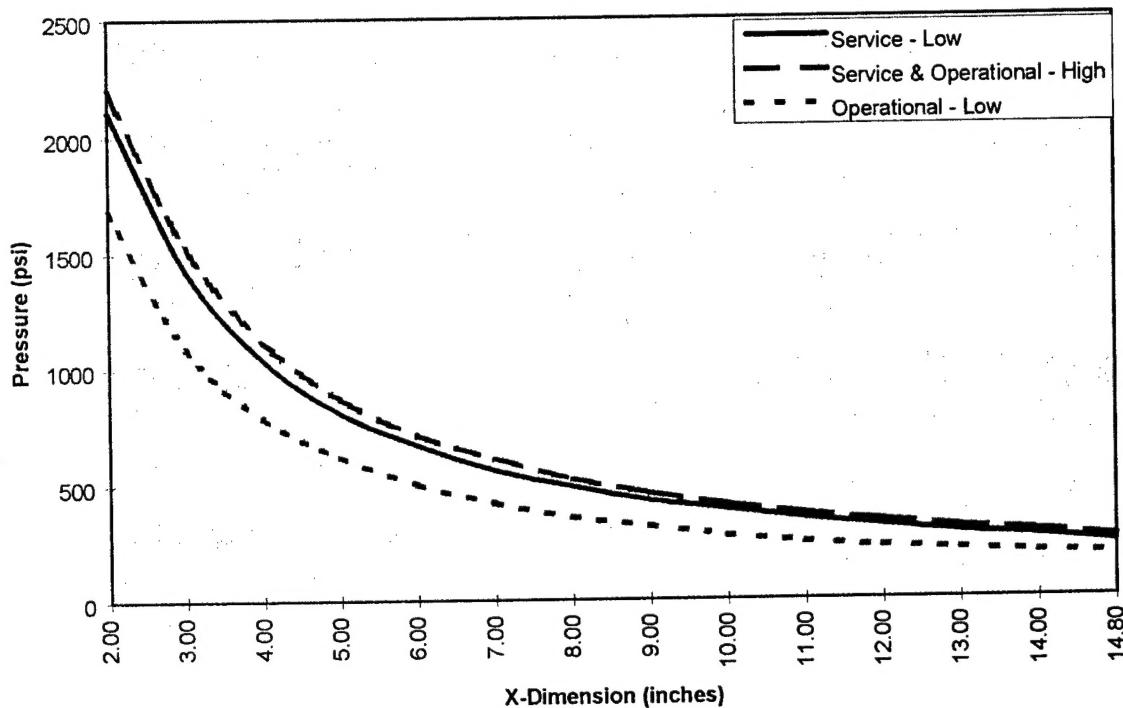
the inner/outer cylinder walls is filled with hydraulic fluid and that the strut is serviced with the proper volume of oil. This will result in the proper dry air/nitrogen volume when charged. Handwritten notes indicate that the hydraulic fluid servicing process should be accomplished two times to ensure the old oil is completely removed and replaced with the new. The dry air/nitrogen servicing is then accomplished by inflating a fully compressed strut to a charted pressure and X-dimension.

On the B737 MLG, hydraulic servicing for a completely deflated strut is accomplished in the same manner as the NLG. In those instances when it is necessary to adjust the oil level in a strut, it is merely deflated and filled with oil until the excess flows out the top; no jacking required. The standard methodology is then used to accomplish the dry air/nitrogen servicing. Dry air/nitrogen servicing is recommended after every 5 to 10 flights to compensate for the oil absorbing the gaseous charge.

For both the NLG and MLG, a 2 point pressure/extension check is accomplished to verify that the strut has proper hydraulic oil servicing. The primary method is to perform dry air/nitrogen serving at an aircraft landing weight to the servicing band. After aircraft loading and fueling, the pressure and X-dimension are checked and compared to the servicing chart. As an alternative, the aircraft can be jacked following the initial pressure measurement to allow the strut to extend approximately 4 inches before taking the second. Any point which falls outside the servicing band indicates that the hydraulic oil quantity is wrong. Below/left of the band indicates too much oil; right/above means too little oil.

The following figure closely approximates the B737 MLG strut servicing chart. It was recreated here to show several things. First, a servicing chart normally only includes high and low service lines which define the borders of the service band. When landing gear struts are serviced, any X-dimension and pressure combination which falls within the band is acceptable as a properly serviced strut. This chart, however, includes a third line which is attributed to dry air/nitrogen absorption. For an in-service aircraft, any combination between this additional line and the upper bound of the service band is acceptable and the strut does not require reservicing. The second point related to this is that it seems to be contrary to Boeing's strut servicing philosophy that this represents a condition with too much oil. The third, and perhaps the most pertinent to this study, point is that this additional line allows for operations with a strut we would consider to be underinflated. The degree and impacts of this level of underinflation have not been assessed.

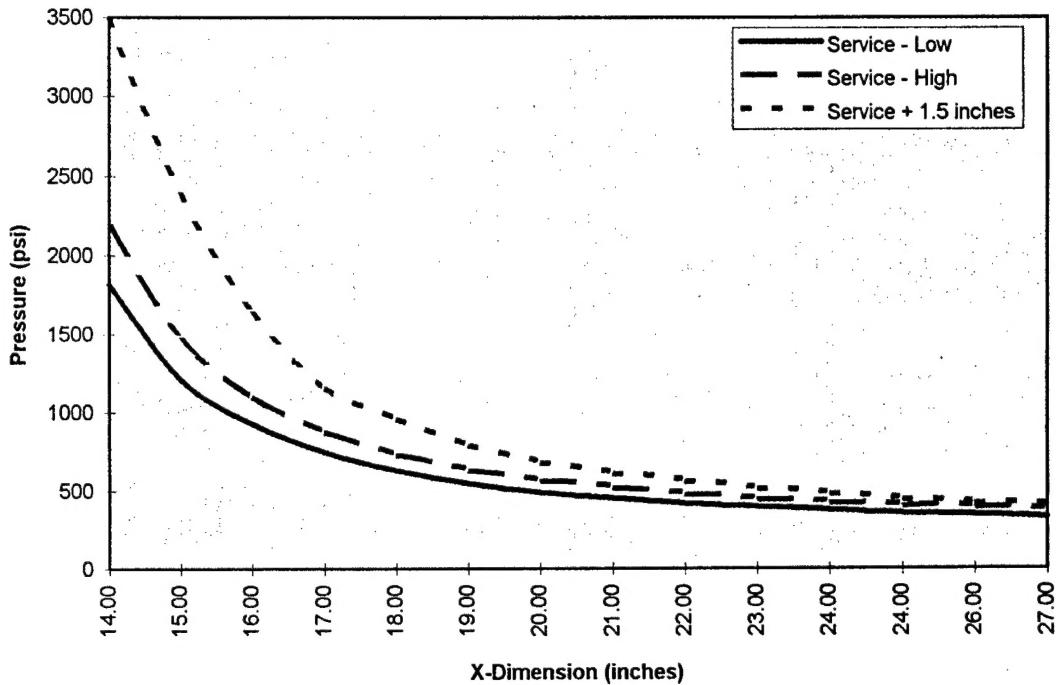
Boeing 737 MLG Strut Service Pressures (Nominal 250 psi @ X = 14.80 inches)



→ B757 Strut Servicing: BCAC also provided a set of briefing charts on B757 strut servicing and curves for both the NLG and MLG. The procedures are fairly straight forward: Deflate the strut, fill with oil, and charge with gas to the proper X-dimension and pressure. It is recommended that the top of the service band be used. However, there is an added step which is unique to the B757; the NLG is then inflated to add an additional 1.00 inches of extension and the MLG is inflated to add an additional 1.50 inches. This is to compensate for the gas absorption which will be experienced. The next strut service pressure check occurs after 5 to 10 flights. If the pressure is below the service band, it is reinflated to be within the band. If it is still above the band, it is not deflated. As with the B737, there is a 2-point pressure/extension check for the B757 to ensure proper hydraulic oil servicing.

The B757 MLG service chart is recreated below. The top curve has been added to show the intentionally over-serviced strut pressures which result by the recommended additional extension. The curve is only an estimation which was created by shifting the BCAC-provided curves 1.50 inches to the right. Due to the increments on the charts, fully extended precharge pressure is estimated to increase by a modest 50-100 psi. Its importance to this study is that there is a documented case intended to counter the ill effects of gas absorption (essentially under-serviced) in landing gear struts. We have not assessed the impacts. It also does not necessarily establish an upper limit for increased precharge concept implementation. Again, there is a need for landing gear manufacturer and/or component supplier participation.

Boeing 757 MLG Strut Service Pressures (Nominal 300 psi @ X = 32.46 inches)



The final parts of information requested from BCAC dealt with recent ADs resulting from structural damage in the vicinity of the MLG. Specifically, they were asked about changes in strut service procedures & pressures and loads sources considered during their failure analyses. Their input is present below in total:

- ⇒ **ADs Impact BCAC Strut Service Procedures/Pressures:** “We are not aware of any recent AD’s which have affected the landing gear shock strut servicing procedures or precharge pressures.”
- ⇒ **Failure Analyses Load Considerations:** “Load cases are combined simultaneously if they can occur as such. Otherwise different load cases, depending on direction and magnitude of the loads, are examined for the worst case ultimate load case at the suspected critical location.

Fatigue analysis generally take into account all loading mechanisms to include ground loads, landing impact loads, flight load envelopes, GAG cycles, etc as experienced by the airplane structure. Testing, analysis and service experience, Boeing design practice and design manual input are used.”